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Amounts of suspended solids and dissolved substances in the middle reaches of the Amazon over the course of one year (August, 1969–July, 1970)

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Introduction

Until very recently (LIVINGSTONE, 1963), scientific knowledge of the composition of the waters of most tropical rivers, even the very largest ones, has been quite sparse. This has been particularly true of the Amazon system, the largest river on earth. After KATZER (1897) published his analyses of several water samples from the lower Amazon, no further investigations were conducted until a relatively few years ago (SIOLI, 1950, 1957; SIOLI and KLINGE, 1961; GESSNER, 1960, 1961 a, 1961 b, 1962; OLTMAN et al., 1963; KLINGE and OHLE 1964; OLTMAN, 1967; WILLIAMS, 1968). Even these, for the most part, were very small investigations, and were often preliminary in nature. Few of the listed authors, for example, were able to collect samples at the same site during both highwater and lowwater phases, and so most can provide no real data for the seasonal or annual fluctuations of the substances in the water. An extensive study by GIBBS (1967) is the most comprehensive report to date on the total salts and suspended solids, and the factors controlling them, in the Amazon and its most important tributaries.

Moreover, the presently available data from various sources on the Amazon were taken from restricted sections of this enormous river. The scattered nature of their distribution further diminishes our capability to interpret data from particular stretches of the river. In such a large body of water, diversity in the characteristics of the water arising from the various geographic subregions it drains is certainly to be expected, even though the river flows through extensive areas with relatively uniform climatic and geographical conditions.

The present study is based on monthly investigations in the period from August, 1969 through July, 1970.¹⁾ Its purpose is to provide additional data on the water quality of the Amazon in its middle reaches. Particular emphasis is given to the magnitude of the amount of suspended solids in the superficial water, the concentrations of several dissolved substances which are especially important as plant nutrients or as chemical buffers, and the fluctuations of these factors over the course of a year. At the same time, this information should increase our understanding of limnological processes in the várzea-lakes (for explic. of „várzea“ see SIOLI, 1957), which are lakes in the annually inundated floodplain of the Amazon. These abundant lakes, which are closely dependent on the river, must eventually assume an important role in the steadily progressing development of Amazonia.

1) I would like to express here my deep thankfulness to my wife Heike for her untiring assistance in carrying out this project. I also thank Sr. Antônio dos Santos, INPA, Manaus, Brazil for conducting the analyses in June and July, 1970.

Collections were made in the Rio Solimões, as the Amazon is customarily called between the Peruvian border and the mouth of the Rio Negro near the city of Manaus. The sampling site was above the mouth of the Rio Negro between the islands Careiro and Marchantheria (Fig. 1), approximately in midstream at the surface of the river. Plastic bottles were filled and returned to the laboratory in Manaus for analysis. It was evident from the studies of GESSNER (1960), OLTMAN, et al. (1967) and own observations that dissolved substances were virtually unstratified with depth, and suspended materials only slightly so. That is, the water is thoroughly vertically mixed except in the vicinity of tributary mouths or lakes. GIBBS (1967) found that, even during higher concentrations of suspended sediments, the suspended solids at 90 % of the depth were only 20 % greater than in surface samples. Therefore surface samples are considered to be representative.

A discussion of the geological background of the Amazon drainage basin will not be presented here, since other authors have already treated the subject (e.g., SIOLI, 1950, 1968; GIBBS, 1967).

Fluctuations in water level at the sampling site correspond to those at the nearby water gauge in Manaus, where they are regularly recorded by the Manaus Harbor Authority. The Authority kindly placed these data at my disposal. Water levels, as well as the times of extreme high and low water levels, vary more or less widely from year to year. These fluctuations can have considerable consequences for all portions of the landscape which are in any way connected with the river. For the limnologist, the minimum annual water level is especially interesting, for it determines the degree of emptying of the várzea-lakes, and thus decisively influences the biotic communities which exist in them. A thorough study of the limnology of a typical várzea-lake of this region will be published elsewhere. In figure 2, the water levels recorded during the year of the present investigation are compared with the mean values for the last ten years. This shows that both the values for extreme water levels and the times at which the extremes occurred were close to those for a „normal“ year. At low water, the difference from the mean level was less than one meter, and at high water, just over one meter. The small temporal shift is also insignificant for the purpose of the present investigation.

For further characterization of the year of study, the monthly sums of precipitation at Manaus are given²⁾. Of course, these records are not representative of the Amazonian drainage basin upstream of the investigation area. No other material was available, however, so these data for Manaus may at least suffice for some insight into conditions of precipitation in the period of the study. These values, too, are compared with the mean amounts for several preceding years (Fig. 3). As one can see from this graph, somewhat less precipitation occurred from September through December, 1969 than the mean for these months over the preceding decade. Thus the dry season was somewhat more severe. On the other hand, the quantity of rainfall in the months January through April, 1970 was greater than the mean for the corresponding period over the previous decade. Thus the rainy season was also rather more extreme, and the annual sum of precipitation for the period from August, 1969 through July, 1970, at 2317 mm agreed surprisingly well with the means for 1960 — 1969 (2307 mm). Overall, the observed differences in precipitation for the individual months in the year of study from the corresponding months of the preceding decade were within the year-to-year variability of precipitation in this area, and therefore cannot be considered extraordinary.

Methods

1. pH Measurement : glass electrode, electric meters WTW pH 54 and WTW pH 390; calibrated with standard buffer solutions of pH 4 and pH 6.9.
- 2) I am grateful to Mr. Pe. Bruno Herzberg, Chefe da Estação Meteorológica de Manaus, for the precipitation records.

2. Electrical Conductivity : Pt electrode, conductivity meter WTW LF 54. The results were expressed as specific conductivity $K_{20} = \mu S/cm$ (adjusted to 20°C).
3. Phosphate : the AMBUEHL and SCHMID (1965) modification of the familiar Molybdenum Blue method.
4. Total-P : procedure of SCHMID and AMBUEHL (1965); it was impossible, however, to standardize the conditions of digestion completely in Manaus.
5. Suspended-P : centrifugation for 10 min. at 4000 rpm to separate suspended solids; analysis of the supernatant after digestion and calculation of the suspended fraction by subtraction from total-P. Dissolved organic-P was defined as the difference between total-P and PO_4 -P plus suspended-P.
6. Nitrite and Nitrate : procedure of GRASHOFF (1964); NO_3^- was reduced by Cd-amalgam to NO_2^- and measured in this state.
7. Total-N : calculated as the sum of Kjeldahl-N plus NO_2^- -N plus NO_3^- -N.
8. Suspended Kjeldahl Nitrogen : analysis of the filtrate (Blauband filter) and subtraction from total-Kjeldahl-N.
9. Chloride : titrimetrically; procedure of MOHR-WINKLER (cited by HÖLL, 1968).
10. Silica : as soluble SiO_2 , photometrically according to ZIMMERMANN (1961).
11. Total-Iron : oxidation from divalent to trivalent Fe with hot, concentrated nitric acid, and photometrically determined with KSCN.
12. Dissolved Iron : procedure as for total iron, applied to filtrate from Blauband filter.
13. Calcium : titrimetrically with Komplexon III (Merck) and HHSNN-Indicator (Merck).
14. Magnesium : titrimetrically with Komplexon III and Erio T-Indicator (Merck) as Ca plus Mg; calculation of Mg by subtraction of the Ca-value obtained by procedure 13.
15. Total Hardness : calculated from the Ca + Mg determination (as German hardness degrees).
16. SBV (Säurebindungsvermögen = acid-binding capacity; alkalinity) : titrimetrically with 0.1 N or 0.05 N HCl, and a composite indicator of methyl red and bromocresol green devised by COOPER (for cooper's indicator, see FREYER, 1964); calculation of HCO_3^- from the SBV.
17. $KMnO_4$ -Demand : titrimetrically, according to the „Deutschen Einheitsverfahren“ (1960).
18. Color : as mg Pt, according to the „Deutschen Einheitsverfahren“ (1960).
19. Turbidity : calculated from the value for extinction through 1 cm, and expressed as the difference between 100 % transmission and the measured % transmission.
20. Suspended solids : filtration of the water samples through constant-weight membrane filters, type 11306 MF 50, pore size 0.6μ , (Sartorius-Membranfiltergesellschaft Göttingen). The filter was dried to constant weight at 110°C. The value for suspended solids was expressed as mg dry weight/liter.

Results

The results are presented in tables 1 and 2 and partly in figures 4 and 5. The relative paucity of dissolved salts in the river, described by the authors cited in the introduction, was generally confirmed by the present investigations. The maximum for electrical conductivity was only $84 \mu S/cm$, and conductivities as low as $45 \mu S$ were observed. Also, the water possessed very slight buffering capacity, as can be seen from the low alkalinities and the corresponding low concentrations of Ca and Mg. In spite of the low buffering capacity, pH was very consistent, and fluctuated only a little around neutrality. Of the rest of the investigated substances, NO_2^- , NO_3^- , and PO_4^{3-} had remarkably low concentrations in the water. Nitrite was never found in more than extremely small amounts; even the maximum of $4 \mu g/l$ lay close to the limits of detection. Several times, this ion was not detected at all. The amount of nitrate varied between 18 and $84 \mu g/l$, and the concentration of phosphate was between <1 and $26 \mu g PO_4-P/l$. Total phosphorus, in contrast, was always considerably greater than free phosphate, and in December, 1969,

total-P reached the relatively high value of $136 \mu g/l$. Rather high values were also obtained for chloride and silica. It can be seen from the values for $KMnO_4$ demand, which varied between 34 and 42 mg/l, that only moderate amounts of oxidizable substances are present in the river. These values corresponded well to those for Kjeldahl-nitrogen. Although NH_3 could not be measured, one may conclude with certainty from the low concentrations of NO_2^- that NH_3 was also low. In view of this, the values for Kjeldahl-N may essentially be considered to represent organic-N. Table 1 also shows that the soluble fraction of organic nitrogen is always greater than the suspended portion.

Table 1:

date	19.8.69	23.9.69	16.10.69	6.11.69	23.12.69	23.1.70	20.2.70	20.3.70	24.4.70	20.5.70	29.6.70	27.7.70
K ₂ O	48,1	53,4	58,9	63,4	83,8	71,4	66,1	66,2	57,4	48,9	47,3	44,8
turbidity	65,9	45,8	61,3	79,7	88,2	79,6	79,9	77,1	59,4	39,5	34,8	36,2
color	40	40	40	29	35	33	42	45	44	70	19	34
N(NO ₂ ⁻)	2	1	3	4	4	1	1	0	1	3	1	0
N(NO ₃ ⁻)	24	40	84	76	71	65	64	43	35	23	18	28
Kjeldahl-N	0,74	0,39	0,40	0,62	0,67	0,74	0,77	0,55	0,56	0,33	0,44	0,40
Kj.N.susp.	0,35	0,08	0,10	0,12	0,26	0,10	0,10	0,23	0,13	0,10	0,08	0,12
N _{total}	0,77	0,43	0,49	0,70	0,75	0,81	0,84	0,60	0,60	0,36	0,46	0,43
P(PO ₄ ³⁻)	6	12	14	26	15	17	12	5	4	12	0	16
P org. gel.	6	14	14	29	20	22	20	9	4	14	22	22
P _{susp.}	20	17	37	37	116	35	70	69	52	44	26	26
P _{total}	26	31	51	66	136	57	90	78	56	58	46	48
Cl ⁻	3,0	5,0	4,0	4,0	3,1	3,0	3,0	2,2	2,6	2,0	3,7	3,7
Si	4,0	4,2	4,5	4,1	3,6	3,6	3,6	4,1	3,8	4,1	3,6	4,0
KMnO ₄ ⁻ demand	38	39	34	40	34	39	40	42	38	41	35	37

For phosphorus, the relation was reversed, as has been mentioned above. This was also true, in general, for iron. The suspended fractions of these were plainly dominant (see fig. 5). Total iron varied between 1.1 and 4.1 mg/l, which are not insignificant concentrations. The present data permit no more precise statements about the degree to which the suspended-Fe fraction was due to insoluble compounds, as opposed to soluble Fe compounds adsorbed onto other suspended particles. The same must be said for present data on phosphorus.

The amount of suspended solids in the water varied during the period of study between 37 and 165 mg/l. In contrast to the nearly constant values in August and September, a significant rise took place in October, which culminated in a maximum for suspended solids in December. The rise in October coincides with the increasingly stronger rainfall in this month, and is therefore apparently related to the onset of the rainy season. Further remarks on this subject will be made in the discussion.

The data presented here clearly show, as has been pointed out several times already, that there were rather strong variations in almost all of the factors included during the period of the study. In figures 4 and 5, several results are presented graphically and compared with the water levels and conditions of precipitation. From these figures, a relationship between suspended solids and the concentrations of total iron and total phosphorus is apparent. Both these substances and the electrical conductivity reached maximal values in December, i.e., at the beginning of the rainy season in this region. The water level was still practically at the minimum. As the precipitation increased in strength and the river rose, the concentrations of substances in the water gradually decreased. This shows that dilution by rainwater is not fully offset by the gain in materials which it washes into the river. At the highest water level, the lowest concentrations of materials in general were measured. As the buffering capacity of the water similarly decreased, and this is best illustrated by the values for SBV and total hardness, pH also decreased slightly at maximum water level.

Discussion

As far as is presently known, a distinct, though not very extreme, decrease in total salt content (i.e., electrical conductivity) takes place along the Amazon from its source region to its mouth. GESSNER's (1960) measurements revealed that the conductivities of two of the primary source rivers, the Marañon (86³)—129 μ S₂₀/cm) and the Ucayali (150 μ S₂₀/cm), are relatively high. In the Solimões near São Paulo de Olivença, he was still able to measure as much as 141 μ S₂₀/cm, and at Codajáz, the conductivity was 74 μ S₂₀. The maximum conductivity in the vicinity of Manaus (Table 1) is of the same magnitude as the last one above. SIOLI (unpublished) found a conductivity of 102 μ S₂₀ in a sample from the Solimões at St. Antônio do Içá on 5-X-59, and one of 90 μ S in the same month at S. Paulo de Olivença. The values found by GESSNER (1960) and OLTMAN, et al. (1964) for the Solimões near Manaus (68 and 45 μ S₂₀, respectively) were in the same range as those during the year of the present study. Since the first of the two measurements was made in January, 1957, and the second in July, 1963, at the beginning and at the end of annual rainy seasons, they fit nicely into the pattern presented here for the year 1969—70. To elaborate, that January must have been among the months of low water levels, while in that July, the water level must have just passed its maximum. Farther downriver, conductivities decrease still more. The junction of the Rio Negro with the Amazon is particularly well marked in this respect (see GESSNER, 1962). At the level of Obidos, that author (1960) measured a mere 27.3 μ S₂₀ in September. According to his data, the conductivity values remain in this range for the rest of the Amazon, from the mouth of the Rio Negro to the sea. There the tides, exerting their influence mainly by impoundment of the river water, cause large fluctuations in the

3) To facilitate comparison, all conductivity values of other authors have been recalculated to a basis of 20°C, whenever they gave the temperature of measurements.

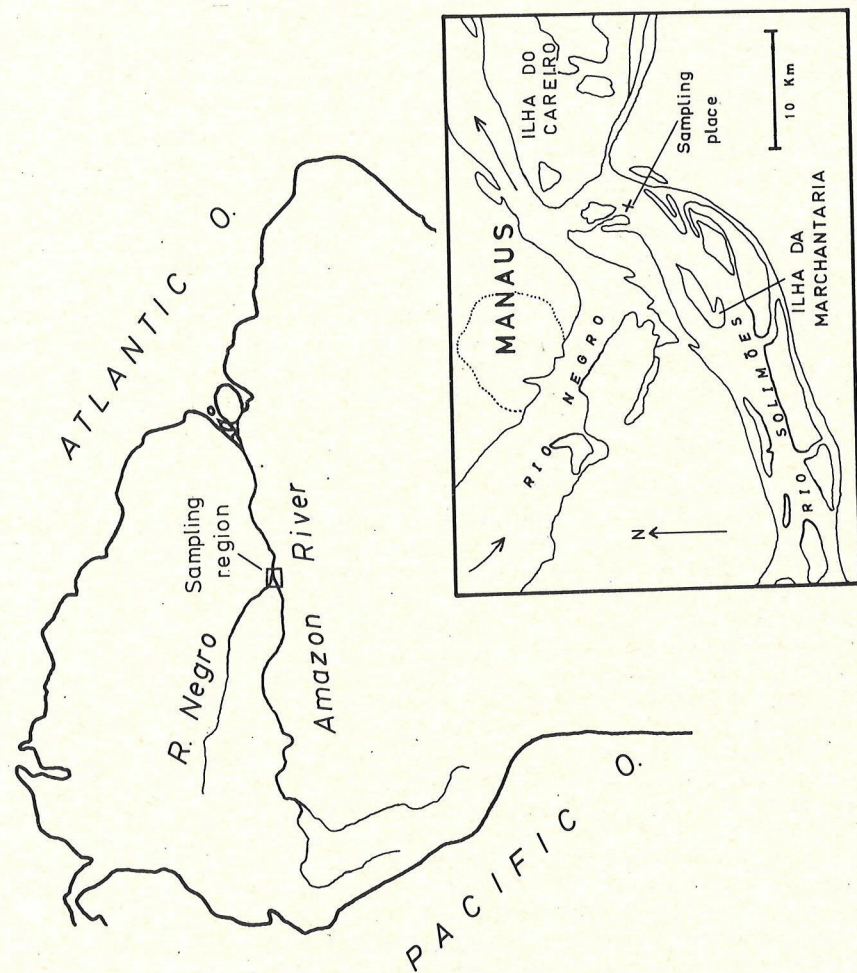


Fig. 1: Map showing sampling region and sampling place.

Table 2:

data	19.8.69	23.9.69	16.10.69	6.11.69	23.12.69	23.1.70	20.2.70	20.3.70	24.4.70	20.5.70	29.6.70	27.7.70
pH	7,0	7,3	7,2	7,2	7,5	7,5	7,4	6,8	6,8	6,7	6,5	6,6
alkalinity (SBV) mval/l	0,38	0,38	0,34	0,55	0,64	0,70	0,64	0,61	0,52	0,46	0,35	0,30
HCO ₃ ⁻ mg/l	23,2	23,2	20,8	33,5	39,0	42,7	39,0	37,2	31,7	28,0	21,4	18,3
Ca ⁺⁺ mg/l	5,45	5,80	6,40	6,30	9,20	9,45	7,30	9,90	7,65	7,40	5,95	6,05
Mg ⁺⁺ mg/l	1,25	1,15	1,70	2,20	1,75	1,95	2,90	1,75	1,15	1,30	1,60	1,50
total hardness = °dH	1,05	1,08	1,30	1,39	1,70	1,78	1,70	1,79	1,34	1,20	1,21	1,20
Carbonate and bicarbonate frac- tion of total salt content (mval %)	71	67	54	77	67	86	85	81	80	86	70	65
mval Ca : mval Mg	2,66	3,10	2,28	1,75	3,21	2,94	1,51	3,47	4,10	2,99	2,24	2,42

conductivity of the Amazon with increasing distance from its source rivers. He investigated the distance to which fresh water penetrates the sea (EGLER and SCHWASSMANN, 1964).

The data of OLTMAN^{*} et al. (1964) also show this tendency towards a decrease in conductivity in the lower reaches of the river. Their values lie in the same range as GESSNER's (1960). Like GESSNER, they also found a transitory, slight increase in conductivity in the Amazon below the mouth of the Rio Madeira.

GIBBS (1967), too, observed a decided drop in the salt content, or electrical conductivity, of the Amazon with increasing distance from its sources. He investigated the most important tributaries in the same period and reported that, with the exception of the Rio Madeira, all of them had a distinctly lower salt content than the main river. This he attributed to the geology of their drainage basins.

A particularly large change in total salt content, as pointed out earlier, occurs at the junction of the Rio Negro and the Amazon. GESSNER (1962) obtained a vertical dropoff in the otherwise relative horizontal curve presented by him for the Amazon. There remains some question about the validity of his method of direct calculation of the quantitative relationships of these two water masses, however. OLTMAN and his coworkers (1964) dispute this problems also, but they were not able to obtain agreement between values for the quantitative proportionality of the two water masses, i.e., the Rio Negro and the Amazon, derived from two sources: theoretical mixing conditions and conductivities; and, direct measurement of discharge. They suggested that physico-chemical reactions between components of these two water masses might occur, among which adsorption and possibly chemical precipitation should be considered.

The situation observed by GIBBS throughout the Amazon and in the tributaries he investigated, i.e., the consistently higher salt content of the water during the dry season in comparison to the rainy season, was confirmed by the present investigations if one assumes, as he did, that December falls within the dry season. The mean rainfall at Manaus in December for the last ten years has been over 200 mm (see fig. 2), so that this month has more accurately been considered a transitional time between dry and rainy seasons there. Nevertheless, during the period from September through December, 1969, there was somewhat less precipitation than the mean over the preceding ten years. In reference to this above, however, it was also pointed out that the difference was relatively minor, and that this was not an unusual divergence of a particular year from the mean for the decade. On the other hand, if the period in question were somewhat drier, both around Manaus and in the larger upstream regions of the drainage basin of the river, some influence on the results of the investigation is of course quite conceivable. REINKE's (1962) study shows that in virtually all of Amazonia, the months from July through October generally have the least rainfall of the year, and that some variation from year to year is, as in the case of Manaus, normal. Unfortunately, there is no better information available on the conditions of precipitation elsewhere in the catchment area of the river during the period of study, so this question can be pursued no farther. For a proper analysis of the individual causal relationships in the present study, several other refinements, including a shorter sampling interval, would also be required. Besides, when one wishes to analyze the relationships between rainfall in the drainage basin of the river and substances in the water at Manaus, one must of course consider the chronological delay between cause and effect, the magnitude of which depends on current speed in the river and distance of separation of causal and affected processes along its course. It is still open to question, then, whether the first heavy rain after the time of minimum precipitation results in an increase in the salt content and the concentrations of other substances in the water. Such a climb in concentration could be due to increased rinsing of materials into the river which had accumulated near the shores during the dry period. BRAUN (1952) mentions an „Uferfaktor“ (= shore factor) in this regard. Elevation in concentration compensates for increasing dilution by rain („Verdünnungsfaktor“ = dilution factor, of BRAUN). After passing a maximum, whose magnitude and time of

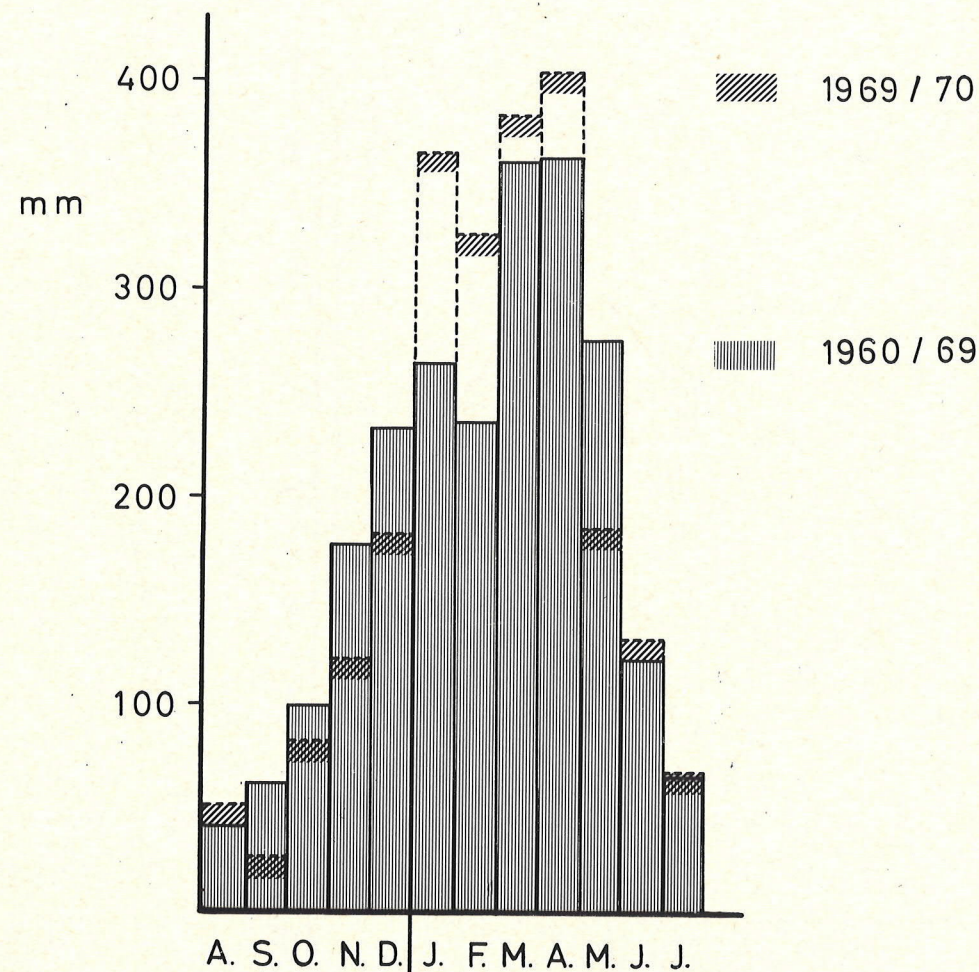


Fig. 2: Comparison between the average river gauges at Manaus during 1960-1969 and the corresponding gauges during the investigation period.

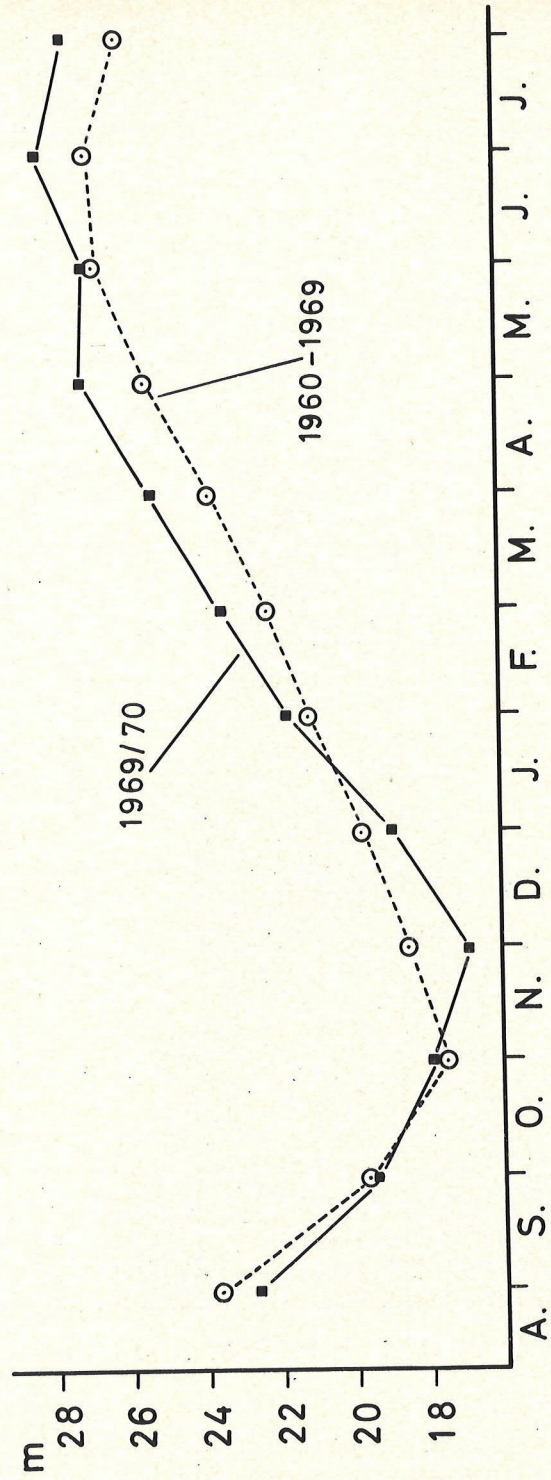


Fig. 3: Comparison between the mean monthly totals of precipitation during 1960-1969 and the monthly precipitation during the investigation period.

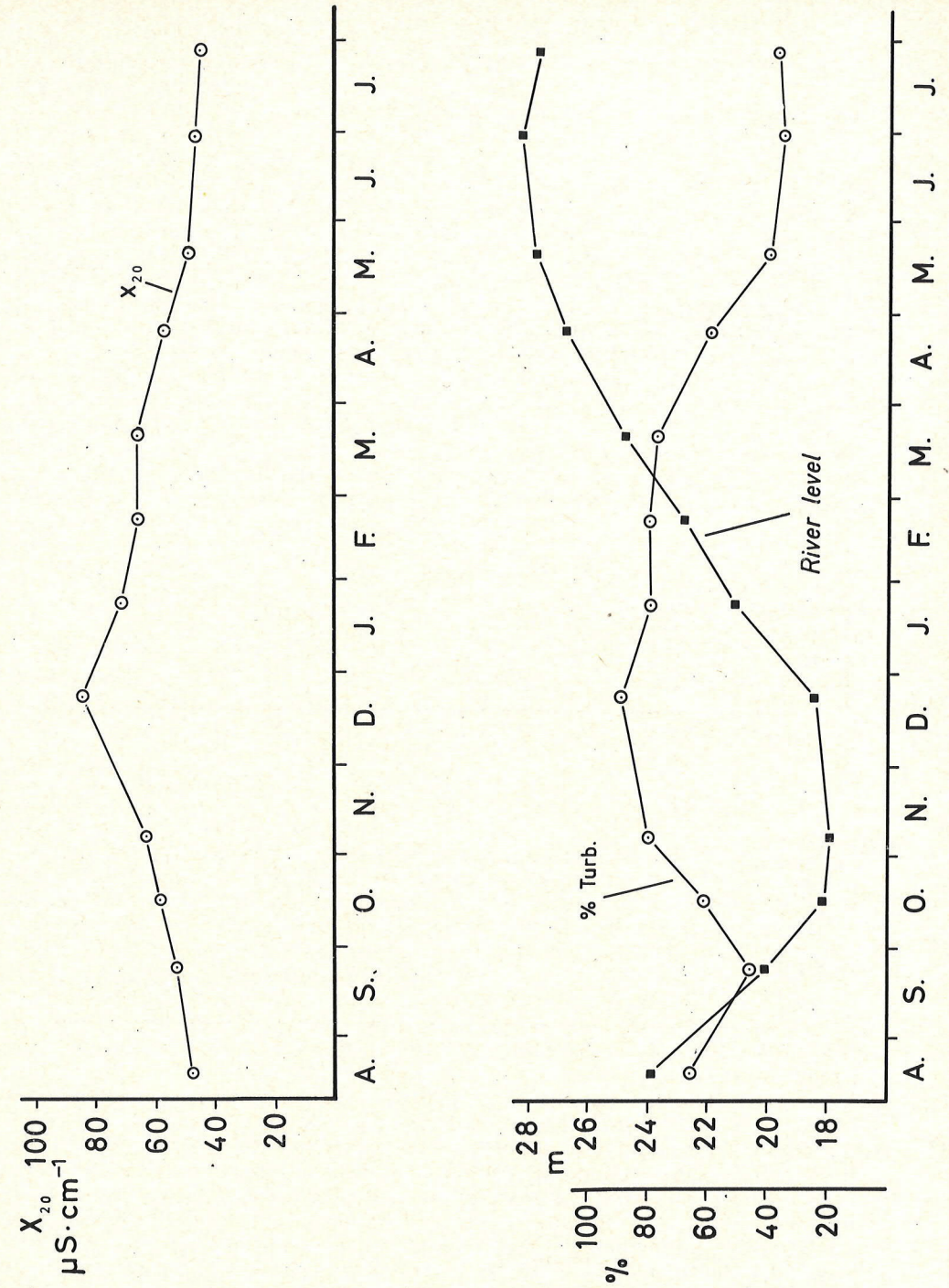


Fig. 4: Electrical conductivity (X_{20}) and turbidity (%) of the water in comparison to the river gouge during the investigation period.

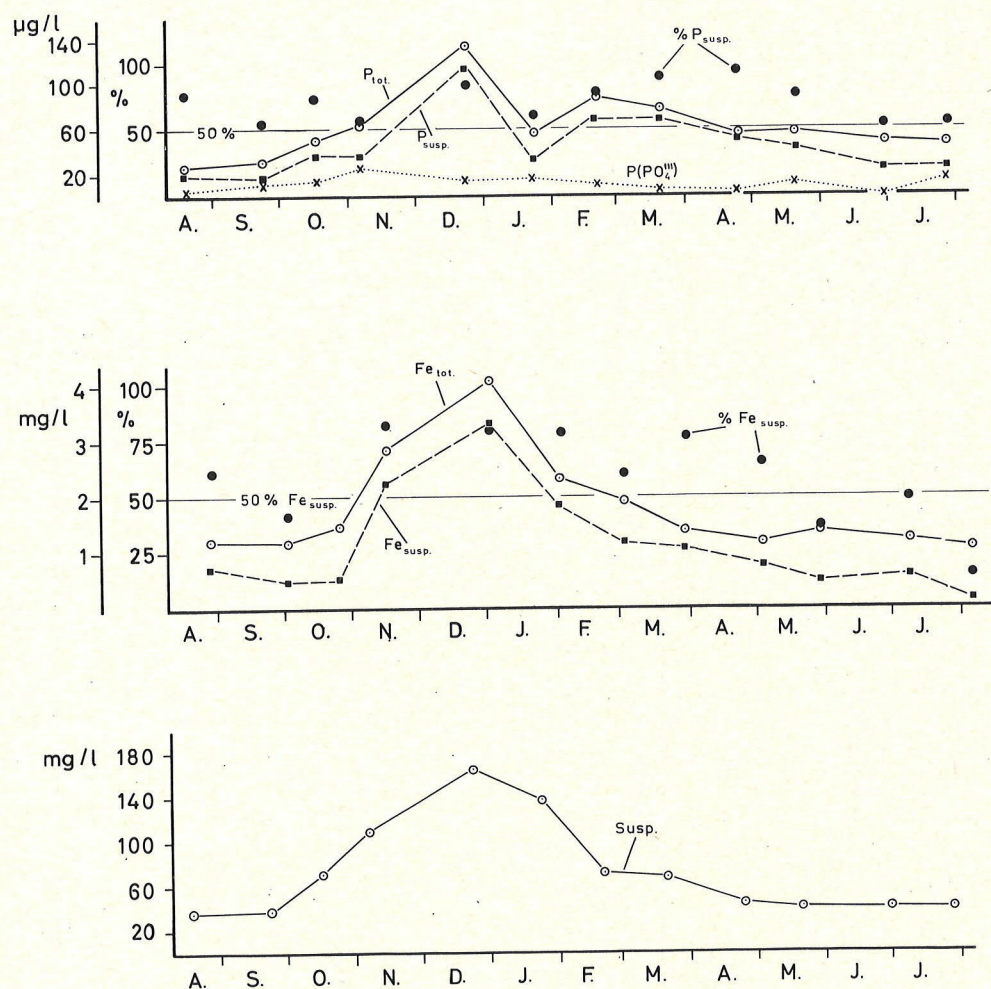


Fig. 5: Concentrations of suspended solids (Susp.), iron (Fe), and phosphorus (P) during the investigation period.
 P_{tot} = total phosphorus ($\mu\text{g/l}$)
 Fe_{tot} = total iron (mg/l)
 P_{susp} and Fe_{susp} = suspended fractions of phosphorus and iron as percent of the total contents.

occurrence depend on the particular conditions at the time, concentrations then decrease with sustained rainfall.

If one calculates the fraction of total salt content of the water due to carbonates and bicarbonates from the alkalinity and electrical conductivity with the method mentioned by RUTTNER (1962), values between 54 and 86 % are obtained (see Table 2). It is further evident from the table that the fraction of carbonates⁴⁾ was at least 15 % higher during the period when the water level was rising than when it was falling in the Amazon. The analytical data for Ca and Mg, of course, reflect the same situation. This fraction of carbonates in the middle reaches of the Amazon is less than those in many central European lakes (ca. 90 %, see RUTTNER, 1962), but still much higher than the fractions in salt-poor waters investigated by others (BIRGE and JUDAY, 1933; ÅBERG and ROHDE, 1942; cited by RUTTNER, 1962). They found fractions of less than 50 % carbonate in many salt-poor lakes. In extreme cases in several Swedish lakes (conductivity ca. 50 μS), only 16 % of the salts were carbonates. It need only be mentioned in passing that certain bodies of water with high salt content also have low carbonate fractions, from geological causes.

Such comparisons have not yet been made for other bodies of water in Amazonia. The author's measurements yielded the following results for examples of a blackwater (Rio Negro) and a clearwater (Rio Tapajóz) river (see SIOLI, 1950, 1965, etc., for discussions of whitewaters, blackwaters, and clearwaters) :

Table 3	Rio Negro (near Manaus)		Rio Tapajóz (just above Santarém)	
	6-VI-68	17-XII-68	14-VI-68	8-XII-69
SBV (mval/l)	0.03	0.03	0.12	0.14
$\mu\text{S}_{20}/\text{cm}$	8.4	8.6	11.9	14.7
Carbonate fraction (mval-%) of total salt content	6	6	92	86

These few numbers suggest interestingly that carbonates are only a vanishingly small proportion of the total ions in the blackwaters, which are extremely low in electrolytes. On the other hand, they are apparently present in „normal“ measure in the similarly electrolyte-low clearwaters. The Amazon tends to belong, at least its middle reaches, in spite of the river's relatively low total salt content, to the type of 'normal' inland waters whose salt content is essentially due to carbonates.

The buffering capacity on the whole is therefore not very high in the middle reaches of the Amazon, yet the pH values are very consistently near neutrality. During the period of study, the pH values were generally higher in the dry season than in the rainy season. When these are compared with pH data from other sections of the river, differences between the upper and lower reaches again come to light. So far, no pH values as high as 7.5 have been reported from the lower Amazon. At Santarém, SIOLI (1957) and SIOLI and KLINGE (1961) found pH's between 6.5 and 6.9. OLTMAN et al. (1964) found pH values in the lower Amazon between 6.6 and 6.34. One of their measurements was even as low as 5.6. Since their corresponding datum for conductivity at this station was also low, only 12.1 μS_{20} , it must be assumed that this sample came from a site where essentially unmixed Rio Negro water occurred. Their description of the site makes such an interpretation quite possible. OLTMAN (1967) later stated, however, that pH could

4) Here and subsequently to be understood as carbonate plus bicarbonate, of which the amount of the latter is heavily dominant at prevailing pH's.

Table 4: Chemical properties of Solimões water (acc. to FITTKAU, unpubl.)

Locality	date	K ₂ O μS ₂ O/cm	pH	(SBV) mval/l alkalinity	Kjeld.N mg/l	N(NO ₃ ⁻) μg/l	P _{tot} μg/l	SO ₄ ²⁻ mg/l	Cl ⁻ mg/l	Ca ⁺⁺ mg/l	Mg ⁺⁺ mg/l	Si mg/l
above Sto. Antônio d. Içá	29.8.61	148	7,3	1,26	0,756	6	85	4,5	2,5	20,3	3,7	7,4
above Lago Catuaí	10.9.61	90	7,1	0,77	0,692	5	45	1,9	1,7	11,5	2,4	6,6
near Ilha de Codajaz	15.9.61	64	6,8	0,54	0,594	8	40	2,2	1,2	7,0	2,1	5,6
upstream of Ilha do Careiro	17.3.61	82	7,4	0,76	1,12	10	79	4,9	2,1	14,3	2,4	5,0
upstream of Ilha do Careiro	4.6.61	57	7,2	0,52	0,605	7	31	1,4	1,6	8,0	1,5	4,7
upstream of Ilha do Careiro	16.9.61	49	6,9	0,45	0,691	5	26	1,6	1,7	7,1	6,1	5,2

climb above neutrality, even in the lower Amazon. In a sample taken near Obidos on 20—XI—63, i.e., at low water level, the pH was 7.1.

In the two headwaters of the Amazon named earlier, GESSNER (1960) determined pH values between 6.67 and 6.85. Farther downstream, he was able to measure pH's up to 7.4 (at S. Paulo de Olivença) and 7.5 (at Fonte Boa). In a sample from the Solimões at St. Antônio do Içá, SIOLI and KLINGE (1961) reported a pH of 7.25. Other samples from the Solimões, with no more specific information on their location, exhibited pH's between 6.63 and 7.38 in investigations by KLINGE and OHLE (1964).

Insofar as may be concluded from these few scattered data, pH in the upper reaches is higher than in the lower, i.e., between the mouth of the Rio Negro and the sea. Not much more can be stated from the available data. In any case, however, it is clear that the whitewater rivers, among which the main example is the Amazon, can possess pH's in excess of the limits set by SIOLI (1965) of 6.2 — 7.2. They may have a pH at least as high as 7.5, for this value has been measured repeatedly since his statement.

Unpublished results, kindly placed at my disposal by FITTKAU, permit an additional comparison (table 4).

Data from the station above the island Careiro agree well in the points discussed above with those presented here for the year 1969—70. They also confirm the results of other authors cited above, in that they illustrate the higher conductivity in the upper Solimões. Seasonal differences for several factors are also evident here. For example, conductivity at the sampling site above the island Careiro was decidedly lower in the dry season (September) than in March, during the peak of the rainy season.

Since, as has been reported before, the majority of the salts dissolved in the water of the middle reaches of the Amazon consists of carbonates, we may guess that other sections of the river also have some relationship between conductivity and concentrations of calcium and magnesium. FITTKAU's values plainly show such a relationship for the Solimões, and the same may be said for the data of KLINGE and OHLE (1964). The latter two authors, however, unfortunately gave no precise information about the time and location of sampling. For this reason, it is difficult to interpret some of their results showing values outside the ranges otherwise known for the Solimões. For example, their samples numbered 10 and 22 had electrical conductivities of less than 20 μS₂₀. Such low salt concentrations are not otherwise known to occur anywhere in the Amazon. It could be another case of incompletely mixed water from a tributary. Two other samples, numbers 9 and 21, had conductivities well in line with the rest of the available measurements.

It may be induced from tables 2 and 4 and from other reports (KATZER, 1897; KLINGE and OHLE, 1964; OLTMAN, 1967) that the proportion of calcium is always much higher than that of magnesium in Amazon water. Thus, the relationship deduced from the high proportion of carbonates between the total salt content and the earth alkalies is especially true for calcium. This allows us to postulate that calcium, similarly to the conductivity, is somewhat reduced in the lower reaches of the Amazon. Confirmation comes from OLTMAN's (1967) table, in which conductivity and Ca-proportion are listed. In his data, one sample (26—XI—63) from Obidos, in the lower Amazon, had an unusually high electrical conductivity: 84 μS (t° = 25°C ?). The Ca concentration of this water was also unusually high for that region: 10 mg/l.

Although the middle reaches of the Amazon, with Ca concentrations of <10 mg/l (see Table 2), may be considered to have calcium-poor water, the equivalent ratios of Ca to Mg up to 4.10 in this region are very similar to those for waters rich in calcium and electrolytes (see OHLE, 1955). Humic substances, which act as ion exchangers and shift this ratio in favor of magnesium in the waters poor in electrolytes and calcium in central Europe (OHLE, 1955, 1964), play a much less important role in the Amazon than might perhaps be expected from the low conductivities. Low humic content in the waters of the central Amazon is demonstrated by the low humus-comparative values of OHLE and KLINGE (1964), and by the values for color (as mg Pt/l) and KMnO₄ demand (Table 1).

Present measurements show that an increase in suspended solids occurs during the rainy season, in a similar pattern to that determined by SIOLI (1957) for the lower Amazon and GIBBS (1967) for the entire Amazon. However, just as with the total salt content, the maximum amounts of suspended solids were measured at the beginning of the rainy season, in December. The increase had begun even in October, which is still in the dry season. Near the true peak of the rainy season, the concentration of suspended solids decreased significantly. The rise in suspended solids during the dry season can definitely be linked with extremely low water levels in lakes which are connected with the river. At this time, sediments which were deposited in the lakes during the highwater phase are resuspended and carried out into the river by effluents from the lakes. In the várzea-lake Lago do Castanho for example at this time (30-X-69) concentrations of suspended solids up to 261.0 mg/l could be observed (SCHMIDT unpublished). This is much more than the Solimões had at the same time (71.0 mg/l at 26-X-69 and 109.6 mg/l at 6-XI-69). GIBBS (1967) has also suggested that this might occur under the conditions described.

Significant relationships were present between the amounts of suspended solids and the concentrations of total iron and total phosphorus (see fig. 5). The total iron concentrations, at 1.1 — 4.1 mg/l, were relatively high, and most of the iron was in the suspended state. This was particularly accentuated when iron was near its maximum value. Therefore, the concentration of dissolved iron varied somewhat less during the year of study, between 0.3 and 0.95 mg/l. Such amounts of iron are remarkable, both in the dissolved and non-dissolved forms. It is tempting to speculate on its significance for judging the nutritional capacity of this water. The iron concentration, however, evidently undergoes relatively large fluctuations in the Amazon. This is shown both by present data on seasonal variations and by the differences reported for different sections of the river. SIOLI and KLINGE (1961) report an iron content of 3.05 mg/l for the Solimões at St. Antônio do Içá, but values as low as 0.36 — 0.38 mg/l from the Amazon at Santarém. OLTMAN (1967) measured only 0.06 — 0.09 mg/l at Obidos, but unfortunately, he did not state whether this referred to dissolved iron or some other fraction. Even should these numbers refer only to dissolved iron, such concentrations as he reports are considerably lower than those in the central Amazon.

Phosphorus follows a pattern similar to that of iron (see fig. 5). Only in January was there notable disagreement between it and total iron and suspended solids levels. The causes of this were not determined. There was always significantly more than 50 % of the total phosphorus in the suspended form, and the phosphate content was more constant, even, than dissolved iron. The difference between total phosphorus and dissolved phosphate plus suspended phosphorus was considered to be dissolved, organically bound P. The tables show that its concentration was quite low all year and varied little. Therefore its quantitative importance was negligible.

The good agreement between both suspended iron and suspended phosphorus fractions and the total suspended solids points to an interdependency of these factors on one another, and to a relationship with the water level and its causal factors. As far as we presently know, by far the greatest portion of the suspended solids in Amazon water consists of inorganic substances (KATZER, 1897; SIOLI, 1957; SIOLI and KLINGE, 1961). Recent investigations (OLTMAN, 1967; GIBBS, 1967) provide the first information on the nature of these mineral constituents, their grain size, etc. They are primarily quartz and various clay minerals, to which the iron and phosphorus could be at least partially bound by adsorption. A few experiments by GESSNER (1960) prove that mud from the várzea-lakes, which essentially consists of sediments from the Amazon, can bind some amounts of phosphorus. GESSNER resuspended this mud and added phosphate solutions to it. Some time after mixing the components of the system, he observed a decrease in the phosphate-ion content of the water in the experiment. On the other hand, when he shook the P-enriched mud with distilled water, P was again released into

solution. From these results, GESSNER concludes that this mud may serve as a buffer for phosphate in the lakes, which takes up or releases P depending on its concentration in the water. The present author has very interesting data on the phosphorus metabolism in a várzea-lake for a full year, which agree quite well with GESSNER's assertions. For example, as the water surface is rapidly receding and superficial sediments are being intensively resuspended, the suspended phosphorus increases considerably to values which are higher than those measured in the river at the same time (SCHMIDT, unpublished). The significance of this process for such lakes is obviously very great.

Since iron exhibits similar behavior, it may be assumed that iron and phosphorus exist in close relationship in the sediments of várzea-lakes. This would certainly be expected, for these sediments must consist largely of deposits of suspended solids from the river. Further investigations are much needed, both because of the great significance of the relationship between iron and phosphorus, and interactions between these elements and other substances in the water. Present data do not allow a more detailed consideration of the problem. In such investigations, an especially important question would be that of the form of the suspended fractions of total iron and phosphorus; whether, or to what extent, they are adsorbed on particles as ions, or present as chemical compounds. Also of special importance, of course, is a better understanding of the role of phosphorus in these complicated processes in relation to its role as a vital nutrient to the phytoplankton in the numerous várzea-lakes, and thus as a limitation on their general productivity. As is well known, the availability of this element to the primary producers is decisive in this respect. When phosphorus is adsorbed on $\text{Fe}(\text{OH})_3$ as the phosphate ion, it is much more readily exchangeable than when it is present as FePO_4 . We do not yet know if algae are able to obtain phosphorus from the latter form at all (GOLTERMAN, 1967). The fact that the water of the middle reaches of the Amazon contains a maximum of only 39 % and usually much less (to <10 %), of its total phosphorus as phosphate, emphasizes the need for further clarification of these questions.

Calcium exhibits no recognizable relationship to iron or phosphorus, as far as can be determined from available data. Coprecipitation of P by excess CaCO_3 , or adsorption of P onto these particles, as discussed at length by GOLTERMAN, would be expected neither in the water of the Amazon itself nor in the várzea-lakes it supplies, for the calcium content of both is much too low. Absorption of P on other suspended particles, in contrast, seems to be favored by low calcium levels. WILLIAMS, et al. (1970) observed a considerably greater adsorptive capacity for P in noncalcareous sediments from North American lakes than in calcareous sediments. The rate of P-desorption was correspondingly less. Binding of phosphorus (and iron) on humus complexes, a significant process in some waters (OHLE, 1964), or on other organic substances, would not be expected in the water of the central Amazon. Neither the relatively low KMnO_4 demand nor the color of the water (as mg Pt/l) permit speculation along these lines.

In general, it may be said that the Amazon in its middle reaches is usually not so extremely low in phosphorus as GESSNER (1960) believed. Such low levels are quite common in Amazonian rivers which drain other geological formations, and in lakes connected to these rivers, and which are generally very much poor in its total electrolyte content (SIOLI, 1950, 1955, 1954; BRAUN, 1952; KLINGE and OHLE, 1964; SCHMIDT, 1971, etc.). It cannot be true for the Amazon itself, even though it is clear from the above discussion of data of other authors (SIOLI and KLINGE, 1961; KLINGE and OHLE, 1964) and those presented here that phosphorus and other vary in quantity in different sections of the river. While the concentration of $\text{PO}_4\text{-P}$ was not high all year, and although the phosphate ion sank to the limits of detection occasionally (see Table 1, 29-VI-70), phosphate also reached a maximum of 26 $\mu\text{g/l}$ (6-XI-69). This is in contrast to usual $\text{PO}_4\text{-P}$ values of <10 $\mu\text{g/l}$. If suspended-P is added to the phosphate, the situation for phosphorus in the central Amazon is still better.

Let us now return once again to the comparison of the most important substances which have been studied in the central Amazon with the annual fluctuation in water level in this region. The co-variation of total salt content with the strongly related factors of carbonate concentration, buffering capacity, iron, and especially, phosphorus works much to the advantage of the várzea-lakes. The annual maximum of all of these factors coincides with the time at which river water floods the lake basins. Unfortunately, it was not possible to include Na^+ , K^+ or SO_4^{2-} in the program of investigation. For sulfate, however, we may refer to FITTKAU's data (see Table 4), which indicate an elevated concentration during the period of rising water level. This would suggest a relatively high initial concentration of this substance, too, in the lakes. A report on the sodium and calcium concentrations in a várzea-lake of this region will be made elsewhere, so that some insight into the changes in these ions in the river will also be achieved.

As the water level of the river drops over the course of the season, and the lakes connected with the main stream drain into it, one can observe a reciprocal effect of the lakes on the Amazon itself. They should be at least partially responsible for the decreasing total salt concentration in the river, because the water originally fed into the lakes by the river at flood stage is gradually diluted by rainwater, to a degree which varies with local conditions. Also, phytoplankton which develops after the suspended particles from the river water settle out in the lakes is transported out into the river as the water level recedes. In spite of the very large flow volume of the Amazon at this point, significant elevations in counts of algae and bacteria in the main channel were observed at the time of sinking water level (SCHMIDT, 1970). Practically the only imaginable cause of such elevations is a contribution of these organisms by lakes and similar biotopes to the river with which they are connected. It is improbable that autochthonous phytoplanktonic production occurs in the Amazon itself, because of its high turbidity, great depth and strong currents. Still other potential influences of the lakes on the river arise from the resuspension of sediments as water levels sink down near the lake bottoms. Resuspension occurs when the depth of the water drops below a critical point, and wave action can stir up the mud and keep it in continual movement. Better understanding of these reciprocal interactions between the Amazon and the lakes, lagoons, etc. connected with it should be an important goal of limnology in Amazonia, for both theoretical and practical reasons.

Summary

Monthly surface samples have been taken from the middle reaches of the Amazon (Solimões) near Manaus above the mouth of the Rio Negro from August, 1969 through July, 1970, a full year. The content of these samples in suspended solids and the concentrations of several important dissolved substances in the water were investigated. The results were compared with the water levels in the river and local patterns of precipitation, which define the seasons in this region.

The results of the analyses showed that the central Amazon River, too, has a relatively low total salt concentration, corresponding to electrical conductivity values from 44.8 to 83.8 $\mu\text{S}_{20}/\text{cm}$. This was combined with a low buffering capacity of the water. Most of the total salts consisted of bicarbonates. Despite the weak buffering capacity of the water, pH values stayed within the range 6.5 to 7.5, very close to neutrality, over the whole year.

The results also showed that almost all of the factors investigated were subject to rather large fluctuations in concentration during the year. For a few factors, the variations were not related in any recognizable way to the other parameters in the study. For others, however, quite distinct relationships to each other, and to water level and precipitation conditions, were obvious. This was especially true for suspended solids, suspended iron and phosphorus, and the total salt content. All these factors had a decided

maximum at the start of the rainy season when the river still stood at a very low level, near the annual minimum, but had just begun to rise again. The concentrations of most investigated substances had their maximum during rising water levels. This situation was naturally very beneficial in the provision of nutrients for the numerous lakes of the várzea, which are directly connected with the river.

In addition, the results of this investigation were compared with other data reported previously for Amazonian water, and new explanations for the decreasing concentrations of many substances in the lower reaches of the river were proposed. Finally, several other important relationships which exist between the river and the lakes, lagoons, etc. connected with it were briefly discussed.

Resumo :

De agosto de 1969 a julho de 1970, portanto durante um ano, foram coletadas e determinadas concentração de material suspenso e teores de diversas substâncias dissolvidas, de mês em mês, perto de Manaus, acima da embocadura do Rio Negro. Além disso, os resultados foram relacionados às variações do nível do rio e às condições de precipitação, em Manaus, como indicadores das estações do ano nesta região.

Os resultados mostram que também neste trecho o rio possui uma concentração relativamente baixa de sais dissolvidos, correspondente a condutibilidades elétricas de 44,8—83,8 $\mu\text{S}_{20}/\text{cm}$. Em relação a esta situação verifica-se uma baixa capacidade de tamponação. A maior parte dos sais dissolvidos é constituída de carbonatos. Apesar da baixa capacidade de tamponação, os valores de pH da água sempre se encontram ao redor do ponto neutro, variando somente de 6,5 a 7,5.

Os resultados da investigação mostram também, que quase todos os fatores estudados sofrem variações mais ou menos grandes durante o curso de um ano. As variações de alguns fatores não mostram quaisquer relações com os outros parâmetros considerados. Outros porém, em especial os materiais suspensos, as frações suspensas de ferro e de fosfato, e o teor total em sais dissolvidos, apresentam um máximo de concentração coincidindo com o princípio da estação chuvosa, quando o rio ainda está muito baixo, mas já recomeçando a subir.

O fato de muitas substâncias apresentarem o máximo anual de suas concentrações durante a época da enchente naturalmente é muito favorável ao abastecimento dos nutrientes das plantas aquáticas nos lagos de várzea conectados com o rio.

Além disso, os resultados desta investigação são comparados com os publicados por outros autores sobre o Rio Amazonas, o que fornece novos dados que indicam diminuições significantes dos teores de muitos dos fatores considerados no curso do rio. Finalmente, algumas relações existentes entre o rio e os lagos, lagoas, etc. a ele ligados são discutidas.

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